

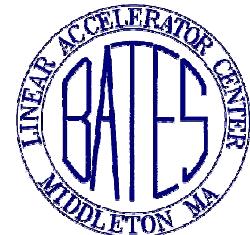
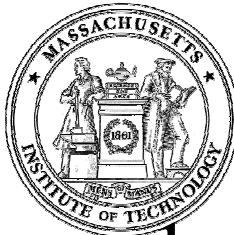
The eRHIC Electron Ring Design Issues

Fuhua Wang

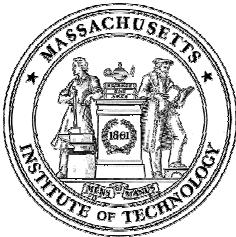
for the MIT Bates eRHIC Team

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eRHIC Collaboration Meeting
BNL, May 29, 2003



1. Matching the electron beam emittance to ion beam emittance for maximum eRHIC luminosities
 - 1.1 Requirements for electron beam emittance regulation.
 - 1.2 New arc lattice design discussion
2. Other initial electron ring issues



eRHIC objects:

E-p & e-ions collisions.

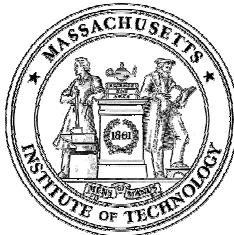
5-10GeV electron; 25-250 GeV proton; 100GeV/u Au.

Luminosity $0.3 \times 10^{33}/\text{sec. cm}^2$ for e-p,
 $10^{30-31}/\text{sec. cm}^2$ for e-Au.

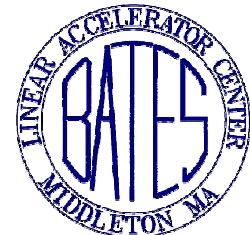
Design Philosophy

Flexibility: Can be optimized to work with varieties of collision scenario.

Reliability: High beam delivery efficiency, high integrated luminosity.

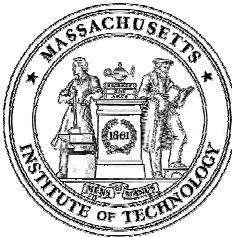


1.1 Requirements for Electron Beam Emittance Regulation



- RHIC ion beam parameters

	P	Au
Energy (GeV)	25-250	100/u
Emittance (Nor. 95%) $\pi\mu\text{m}$	20-12	15-3 (with e- cooling)
Number of bunches	360	360
Bunch population[10^{11}]	2	0.01
Beam-beam parameter	0.005	0.005
Angular size at IP (urad)	160	160



Achievable luminosity

- Luminosity limit:

$$L = F_c \frac{NeNi}{4\pi\sigma^*} \quad \Rightarrow \quad L = F_c \xi_e \xi_i \sigma_e^{*} \sigma_i^{*} \left(\frac{4\pi\gamma_e \gamma_i}{r_e r_i} \right)$$

Under the three constraints:

- Beam-beam parameters (round beam)

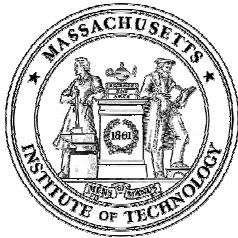
$$\xi_e = \frac{N_i}{\epsilon_e} \left(\frac{r_e Z}{4\pi\gamma_e} \right) \quad \xi_i = \frac{N_e}{\epsilon_i} \left(\frac{r_i (v/c)_i}{4\pi Z} \right)$$

- Round beam collision $\sigma_e^* = \sigma_i^*$

- Angular apertures

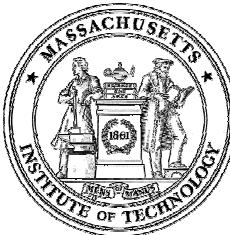
$$\sigma_i^* = \sqrt{\frac{\epsilon_i}{\beta_i^* (\beta\gamma)_i}} \quad \sigma_e^* = \sqrt{\frac{\epsilon_e}{\beta_e^*}}$$

$$And \quad \sigma^* \leq \frac{1}{n} \frac{a}{d} \quad n_i \approx 6, \quad n_e \approx 12,$$



An Web application for the optimal emittance calculation (See Bates Home Page):

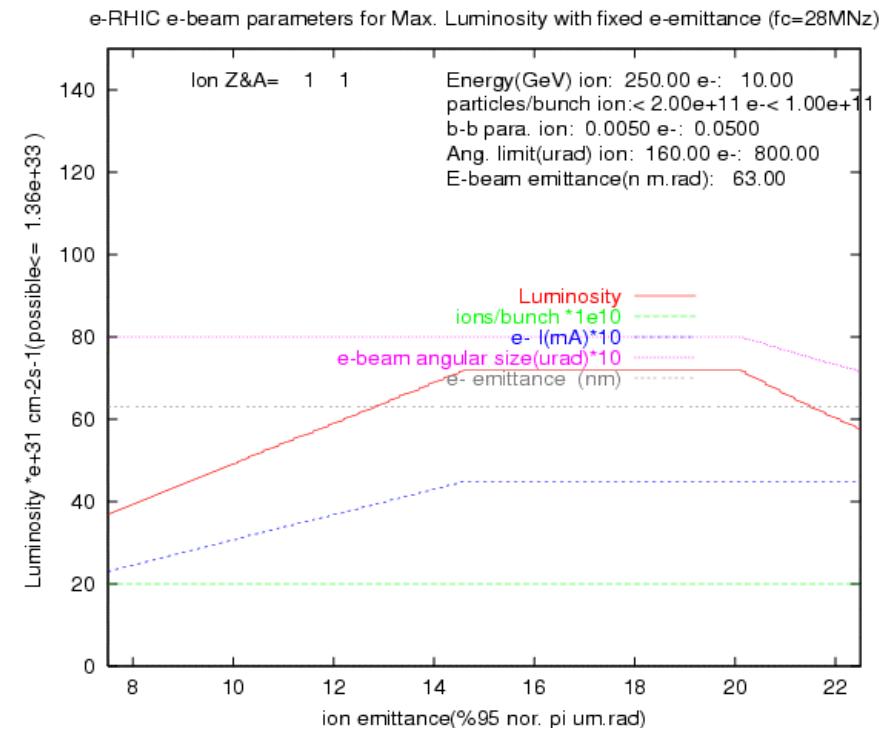
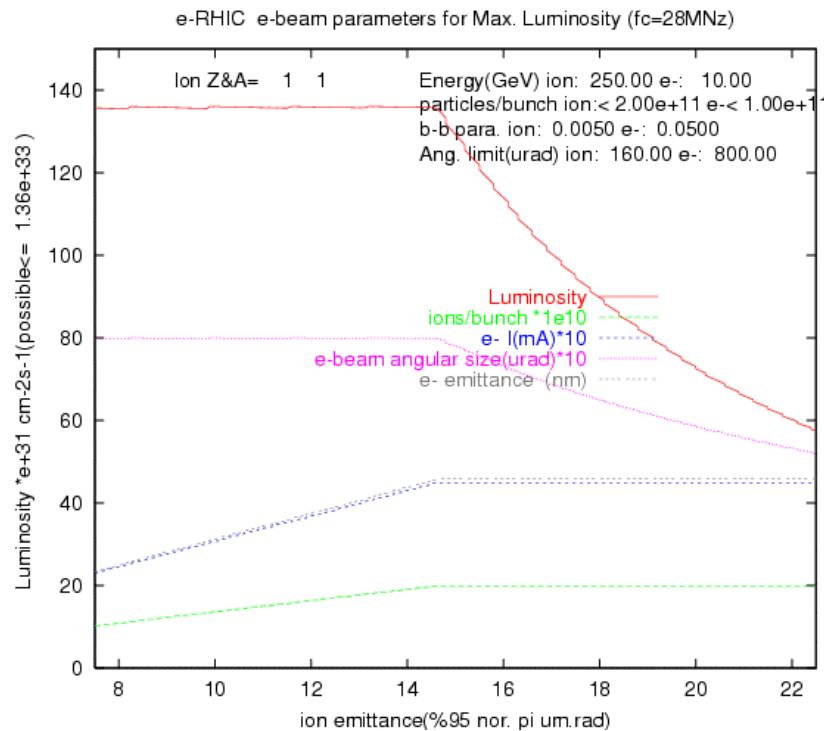
<http://babbel.lns.mit.edu/cgi-bin/fw/eic/eRHIClum.weblum.cgi>

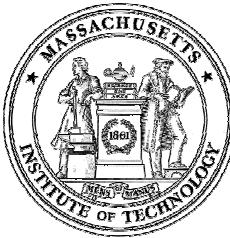


250 GeV proton vs. 10 GeV electron (Medium e⁻ emittance ~ 40 nm)

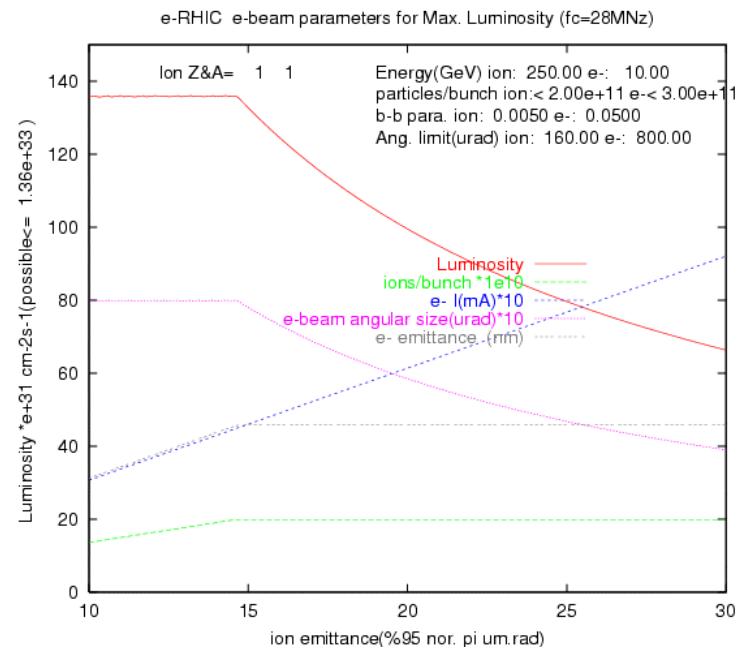


- Optimal e⁻ emittance
- Fixed e⁻ emittance

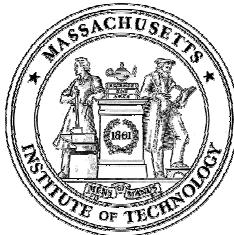




250 GeV proton vs. 10 GeV electron (with higher electron beam current)



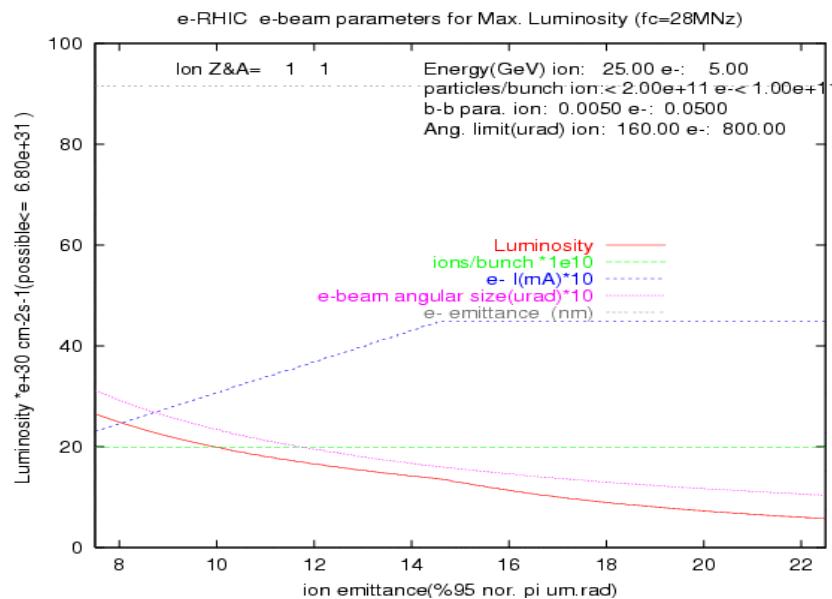
- What about to increase e beam current
<1.35 A
- It only helps for very high proton emittance.
Not worth it!



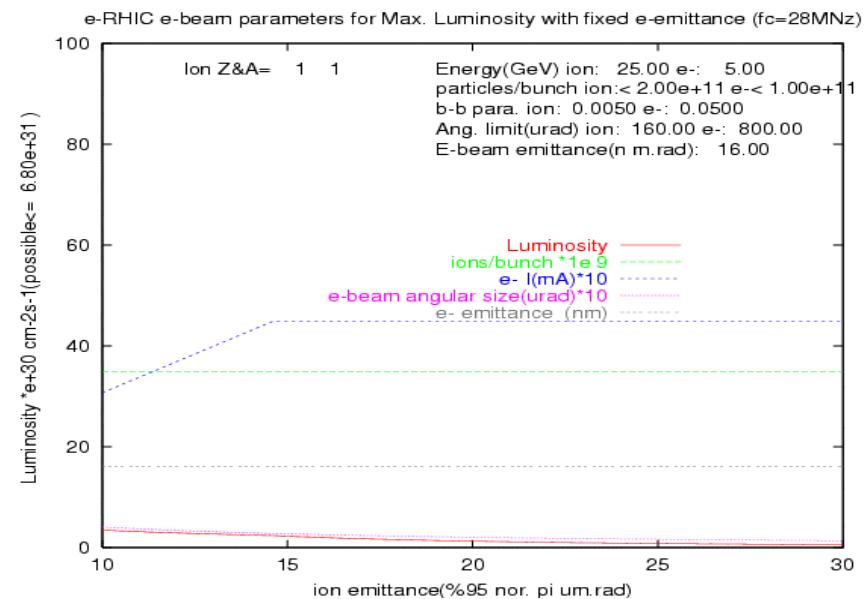
25 GeV proton vs. 5 GeV electron (High e⁻ emittance for larger ion beam size)

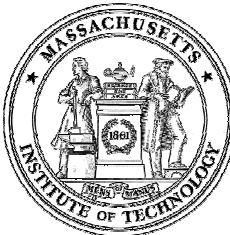


- Optimal e⁻ emittance



- Fixed e⁻ emittance

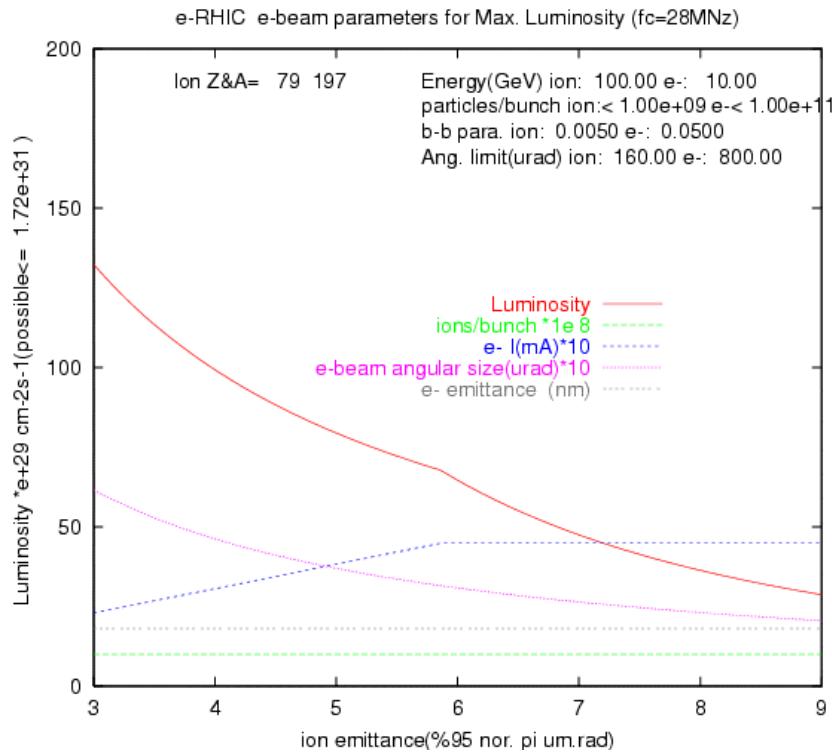




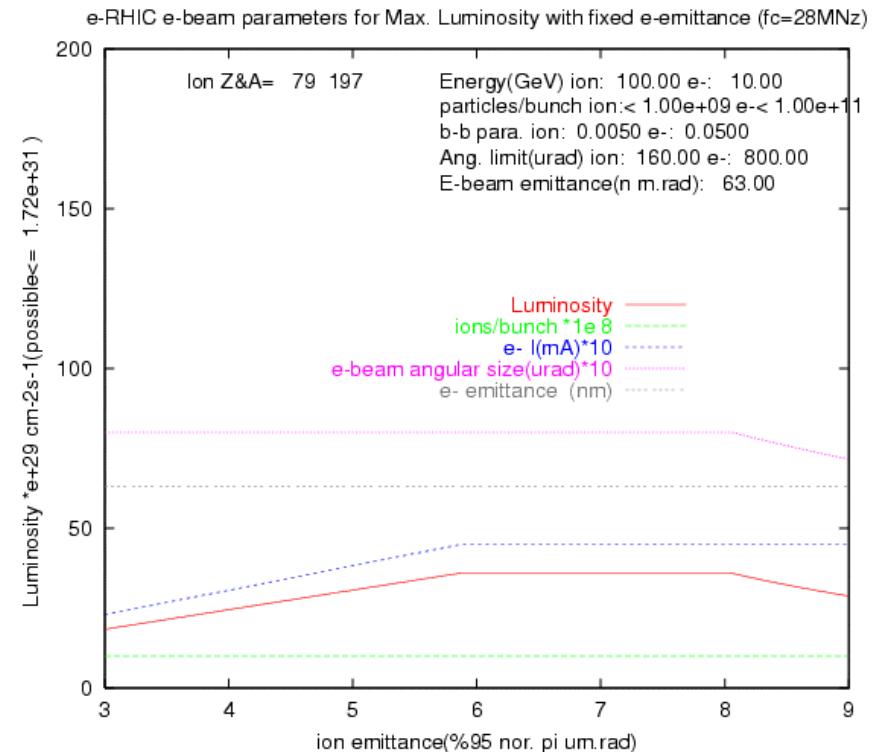
100 GeV/u gold vs. 10 GeV electron (Small e- emittance ~ 18 nm)

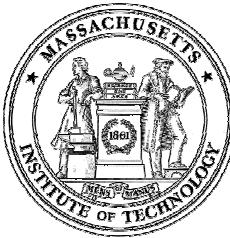


- Optimal e⁻ emittance



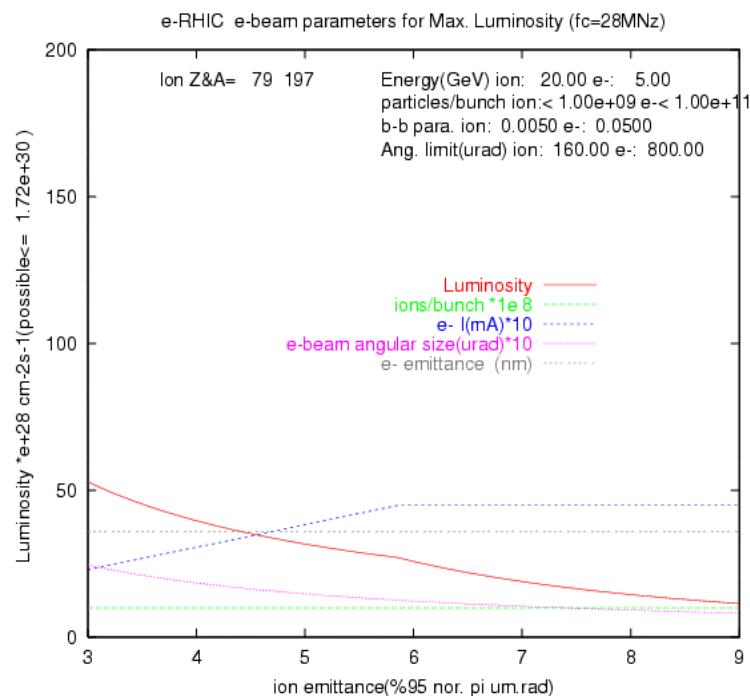
- Fixed e⁻ emittance



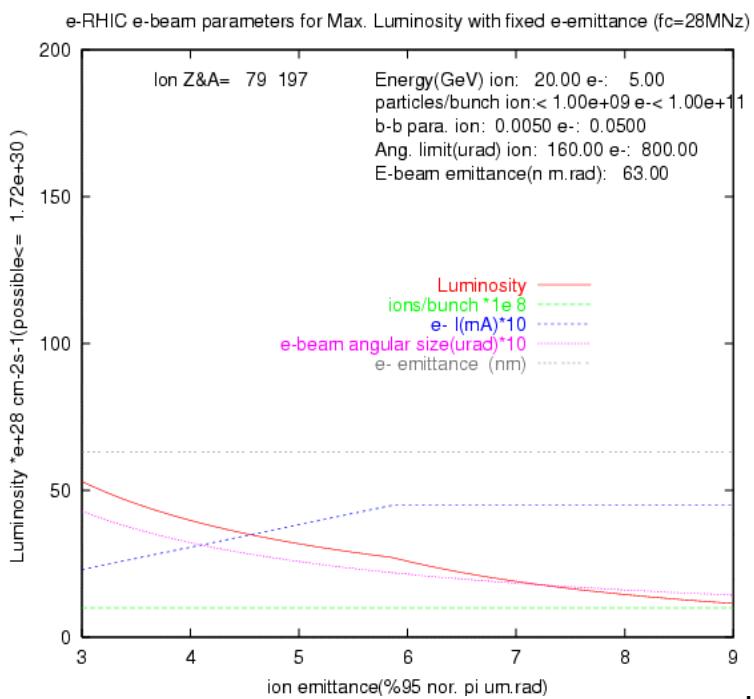


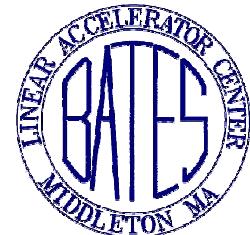
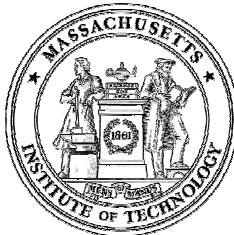
20 GeV/u gold vs. 5 GeV electron

- Optimal e⁻ emittance



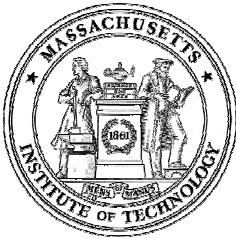
- Fixed e⁻ emittance





Desired Electron beam emittance regulation range

	P	Au	e ⁻
Energy (GeV)	25-250	100/u	5-10
Emittance(95%) $\pi\mu\text{m}$	20-12	15-3 (with e- cooling)	
Bunch population[10 ¹¹]	2	0.01	1
Beam-beam parameter	0.005	0.005	0.05
Angular size at IP (urad)	160	160	800
Optimal electron beam emittance (n m-rad)	46-38 (10GeV e- vs. 250 GeV P) 92 (5GeV e- vs. 25 GeV P)	18 (10 GeV e⁻)	



Optimizing electron beam emittance:

- For maximum luminosity
- Relaxing tough requirements to other beam parameters: high bunch charge, small beta functions at interaction point etc.

This is especially true when the ion emittance is in the lower edge of the RHIC ion emittance range.

Required range:

18 - 360 nm for an electron ring lattice at 10 GeV.



1.2 New arc lattice design Discussion



1.2.1 Ways to adjustment electron ring beam emittance Synchrotron radiation Integrals:

- Formulas

$$I_1 = \int \frac{\eta}{\rho} ds, \quad I_2 = \int \frac{1}{\rho^2} ds, \quad I_3 = \int \frac{1}{|\rho^3|} ds$$

$$I_4 = \int \frac{(1-2n)\eta}{\rho^3} ds, \quad I_5 = \int \frac{\left(\gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2\right)}{|\rho^3|} ds$$

Energy spread, Emittance

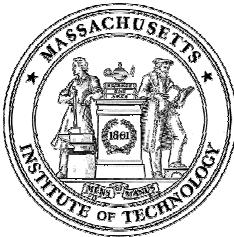
$$\sigma_\varepsilon^2 = c_q \gamma^2 \frac{I_3}{2I_2 + I_4}, \quad \varepsilon_x = c_q \gamma^2 \frac{I_5}{I_2 - I_4} \quad c_q = 3.84 \times 10^{-13} m$$

Momentu4m Compaction, RF acceptance

$$\alpha = \frac{I_1}{C} \quad \varepsilon_{rf} = \pm \left[\frac{2U_0}{\pi \alpha h_{rf} E} \left[\sqrt{q^2 - 1} - \cos^{-1}(1/q) \right] \right]^{1/2}$$

Damping Partition numbers:

$$J_x = 1 - \frac{I_4}{I_2} \quad J_\varepsilon = 2 + \frac{J_4}{I_2}$$



- Ways to adjust emittance:

In the arcs: (to reduce or increase)

changing dispersion η , betatron oscillation in the bends.

RF frequency shift-> electron energy->damping partition numbers,

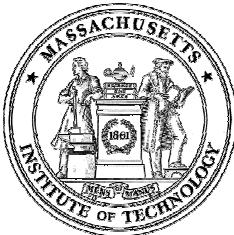
Wigglers: (to increase)

Lower energy

$$\frac{\varepsilon}{\varepsilon_0} = \left(1 + \frac{I_{5w}}{I_{50}}\right) / \left(1 + \frac{I_{2w}}{I_{20}}\right)$$

Heat beam up (to increase) with gas target?

Also for round e- beam. But non linear spin resonance, beam life time, ion instability...?



1.2.2 ARC Lattice Style



a)

FODO: Collider rings.

PEPII HER ring , eRHIC e-ring 2002, HERA

Arc is mainly for bending.

Simple compact FODO structure in the arc.

Dispersion suppressor to the straight sections.

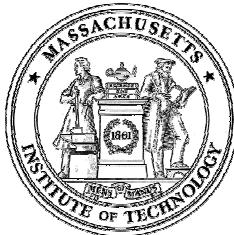
b)

Expanded Chasman-Green type : Third Generation Light Sources

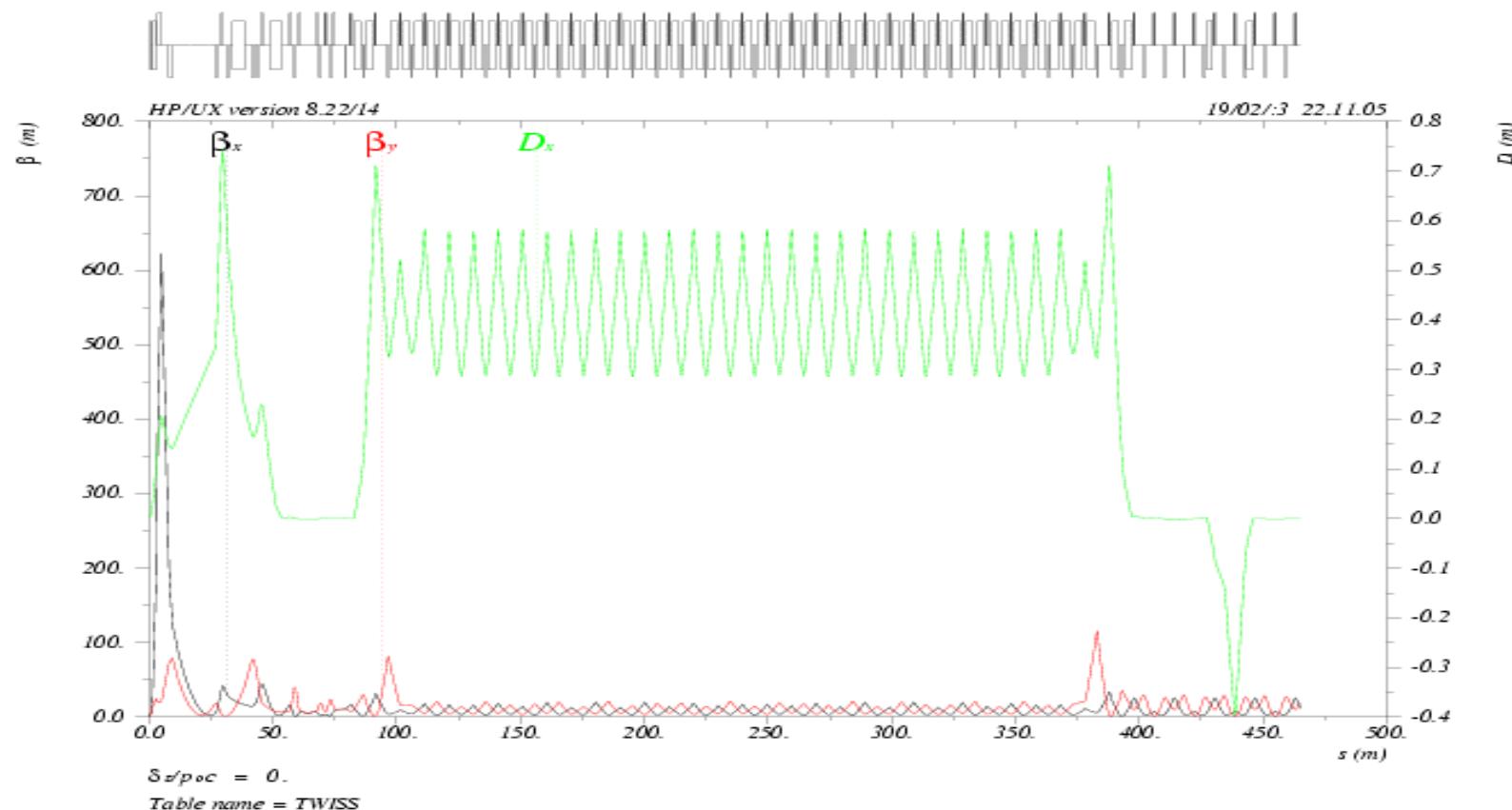
Normal cell: Double Bend Achromat(DBA) or Pseudo DBA, beta,eta functions matching on both ends for insertion devices. **Low emittance.**

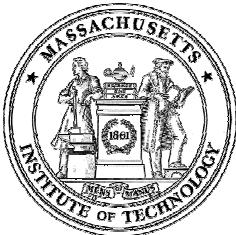
Strong focussing: higher chromaticity->stronger sextupoles -> dynamic aperture reduction.

Harmonic sextupole correction applied at ESRF, BESSYII to obtain large dynamic aperture.



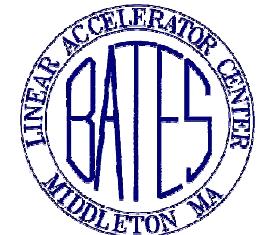
The 2002 eRHIC electron ring lattice (BINP-MIT Bates, Half length)



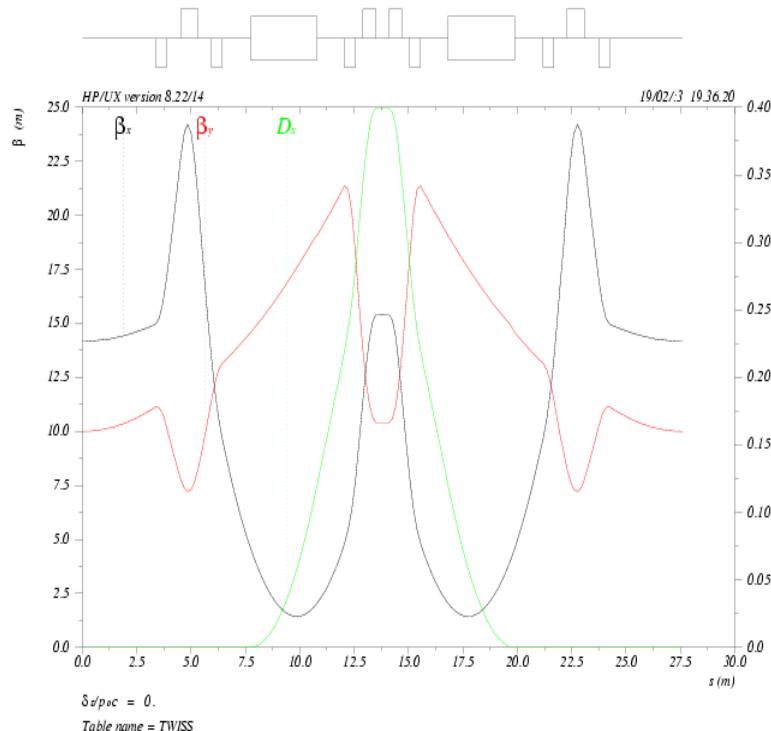


b)

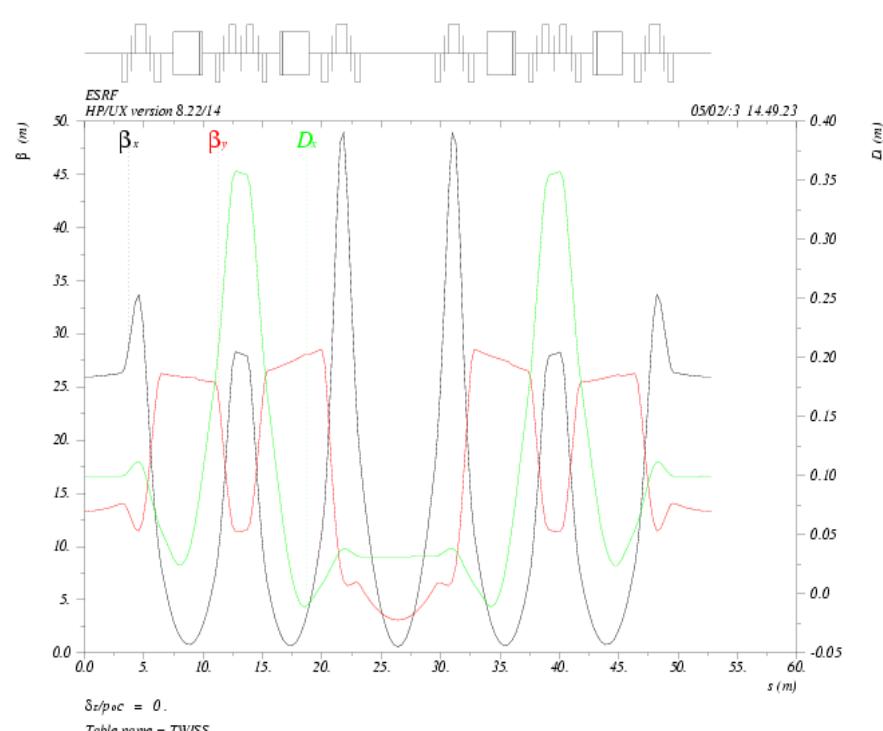
The APS and ESRF normal cells

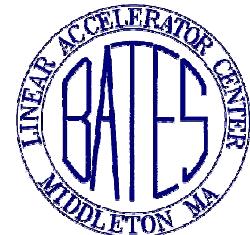
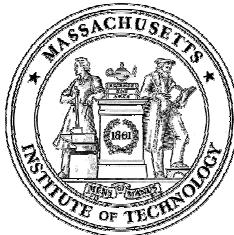


- **APS Cell (8.2 nm.rad at 7 GeV)
Double Bed Achromat(DBA)**



- **ESRF Cell (4 nm.rad at 6.0GeV)
Four Bend Pseudo-achromat**





c) The UK DIAMOND light source (2006) design.

3GeV, 560.4m,

$\epsilon_x = 2.0 \text{ nm}$,

Natural chromaticity:-100,-42 !

- Pseudo-Double Bend Achromat
=> small emittance
- Large dynamic aperture (50σ) with harmonic correction sextupole families.

Examples of dynamic aperture correction simulation

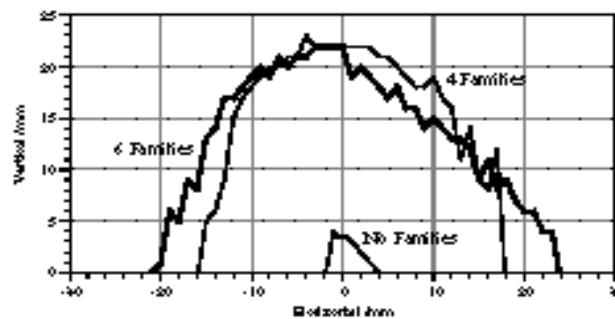
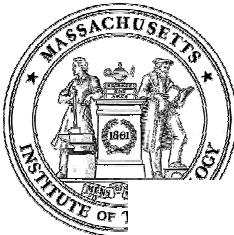


Figure: 5 Dynamic aperture of the nominal working point for the four-family and six-family solution for on-momentum particles, tracking for 1000 turns. The dynamic aperture with no harmonic sextupoles is also shown.



Examples of emittance adjustment



- ❖ HERA(FODO)

41--(phase increase)-->30--(rf fre. shift)-->20 nm

- ❖ ESRF(Light Source)

7nm(DBA) ---> 4nm

(Dispersion pattern, achromat=> Pseudo achromat with finite dispersion at insertion straights;

Natural achromaticity ~-120,harmonic sextupoles added for dynamic aperture)

Light source type lattices are flexible for emittance adjustment.

However usually “upgrade” means go for smaller emittance .

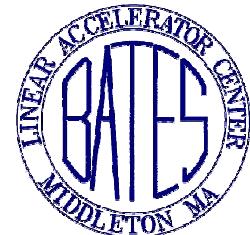
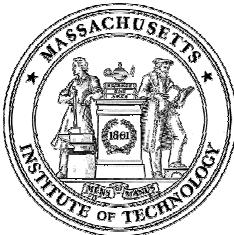
Constrains:

β, η matching at insertion devices.

High natural chromaticity due to strong focussing.

Noticed:

It is hard to reduce emittance for an already existed lattice.



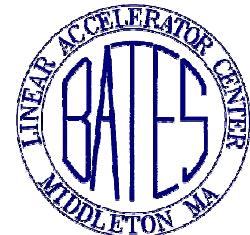
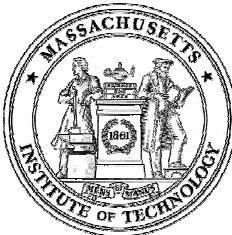
1.2.3 The new arc lattice design

Light source type, no insertion matching constrains, lower emittance possible, very flexible for emittance adjustment.

**For low emittance: Strong focussing causes larger chromaticity, high sextupole strength.
Concerns: higher sensitivity to errors, dynamic apertures.**

Noticed :

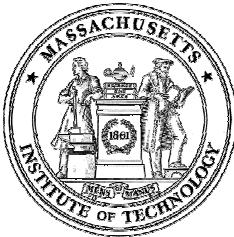
- a) Need to set basic cell structure for low emittance configuration at beginning.
- b) Have to run medium emittance in **most** time.



Arc lattice cell structure, variable configurations.

- ❖ **Normal DBA or Pseudo-DBA** cell.
Low minimum emittacne (“normal achromat”). Proper tune range: ϵ_x 8-20 nm
- ❖ **Four bend achromat** cell. Very flexible for emittance adjustment and high RF acceptance. Proper emittance range: ~16-60 nm.
- ❖ **Hybrid (“Expand FODO”), Non achromatic.**
Emittance can be change from ~20-160 nm, by adjusting dispersion pattern and beta functions. Higher momentum compaction α , less RF acceptance as $\epsilon_{rf} \propto \alpha^{-1/2}$.

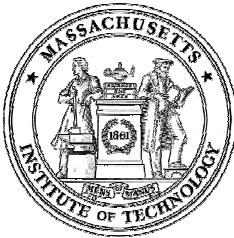
However the need for very large emittance happens in low electron energy region, so it will not impose extra RF voltage requirement.



- Optical Matching from arc to straights: one physical cell .

Circumference considerations:

- Linear radiation power limit < 15 KW ?
 - Low emittance boundary ~ 10 nm? (96 DBA cells)
 - Magnet design limits (Q, S strength).
 - Cost
 - And 28 MHz collision frequency etc.
- ➔ ~< 1/3 of RHIC ring length.

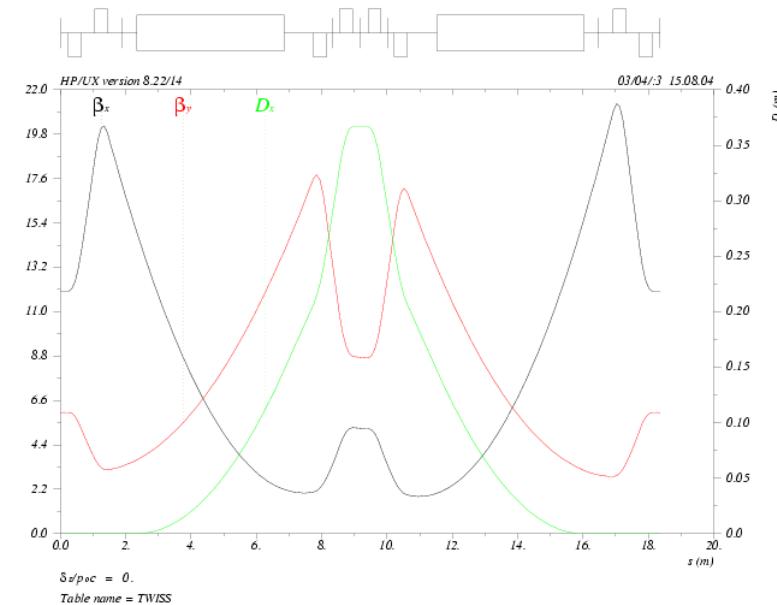
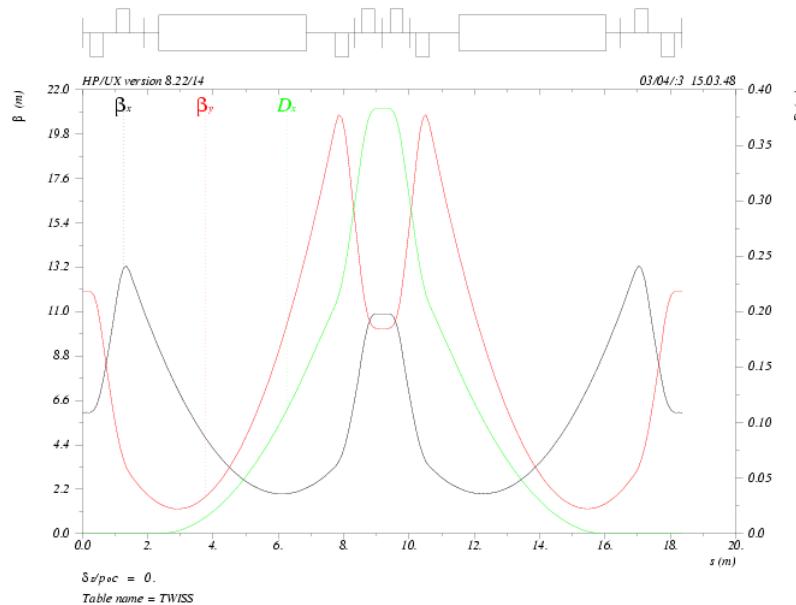


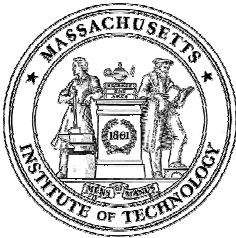
The new arc lattice cell models

Circumference ~ 1200 m

Double Bend Achromat, $\alpha \sim 0.35 \times 10^{-3}$

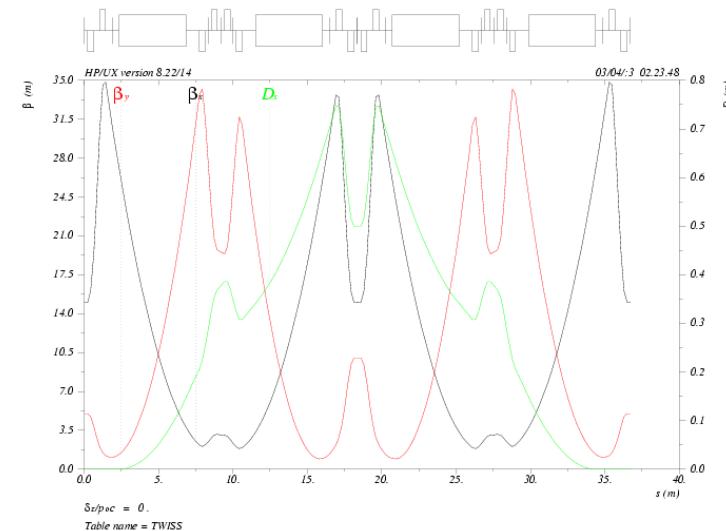
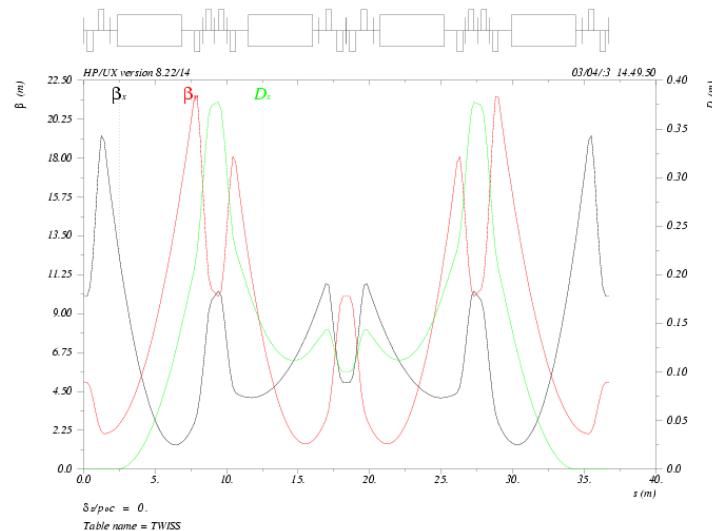
- Low emittance, $\varepsilon_x \sim 10$ n m.rad, at 10 GeV. $\xi_x = -112$, $\xi_y = -64$.
- Medium emittance $\varepsilon_x \sim 24$ n m.rad, at 10 GeV. Chromaticity correction?

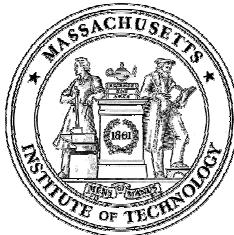




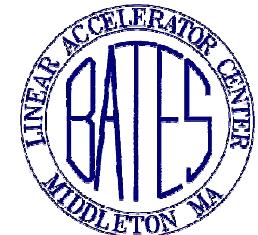
Four bend Achromat

- Low emittance, $\epsilon_x \sim 16 \text{ n m.rad}$, at 10 GeV. $\alpha \sim 0.95 \times 10^{-3}$
- Medium emittance, $\epsilon_x \sim 57 \text{ n m.rad}$, at 10 GeV. $\alpha \sim 0.19 \times 10^{-2}$

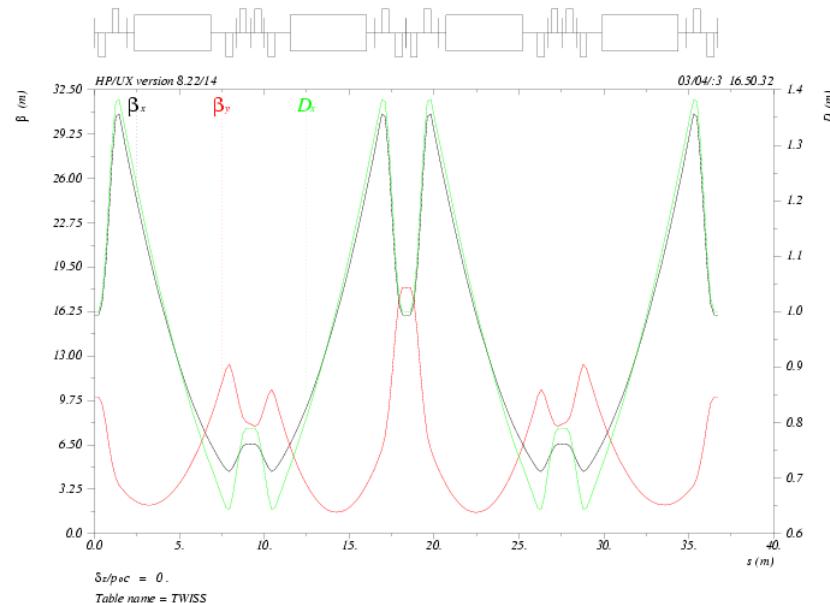


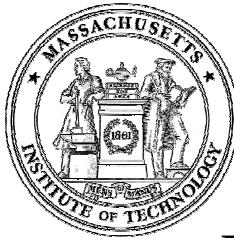


Hybrid for high emittance

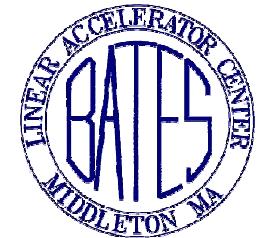


Hybrid (“Expand FODO”), non achromatic. ($\epsilon_x \sim 20\text{-}160 \text{ nm}$)
 $\epsilon_x \sim 158 \text{ n m.rad. at } 10 \text{ GeV, } \alpha \sim 0.68 \times 10^{-2}$

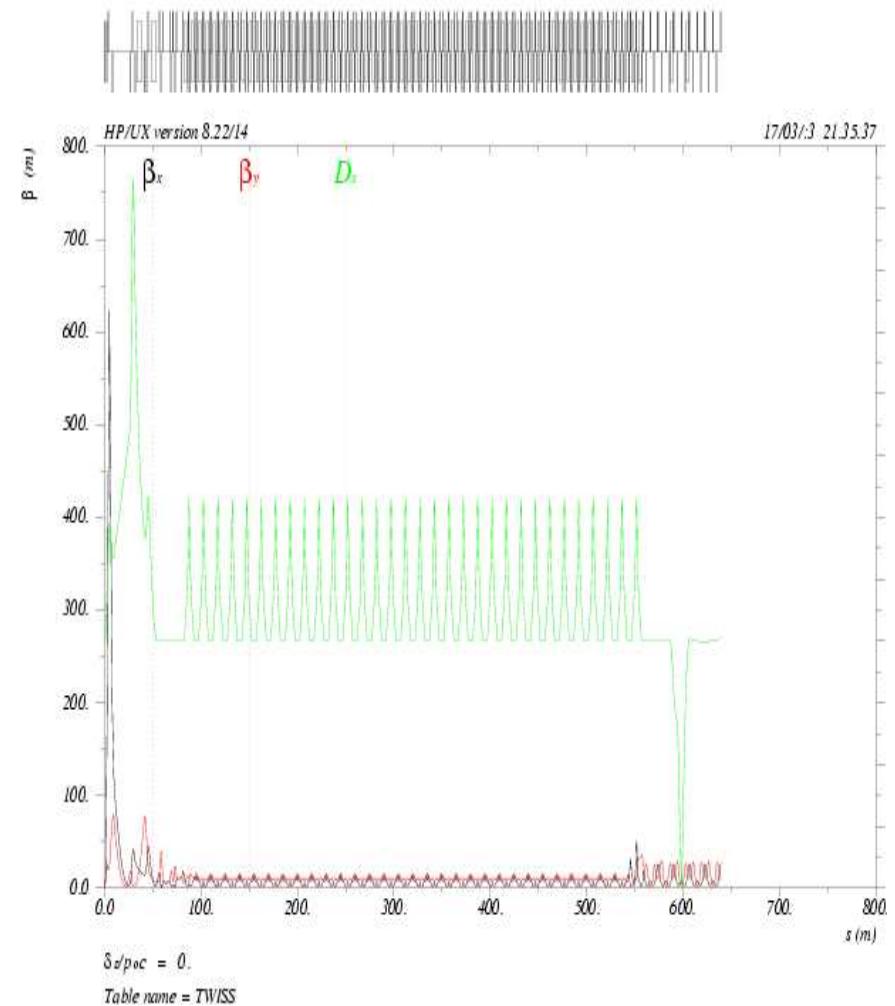
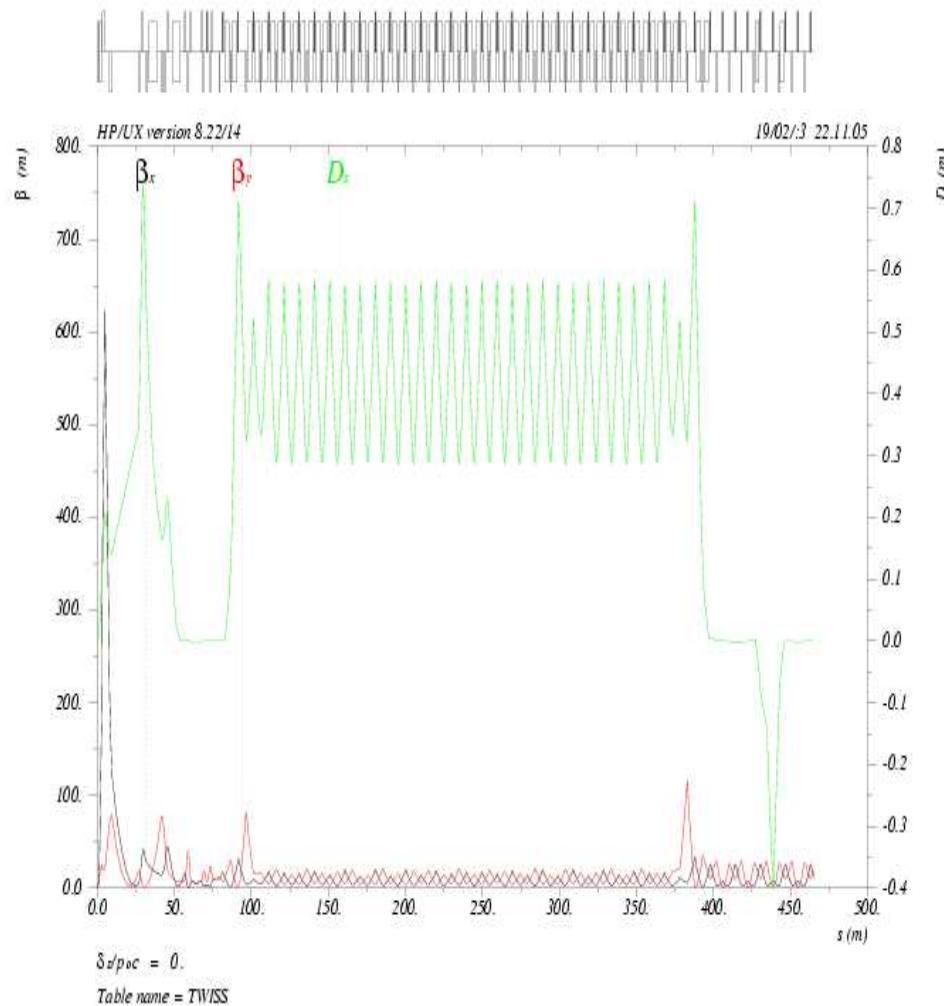


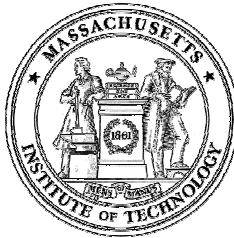


Comparison: BINP-Bates 2002/New (arc) lattice

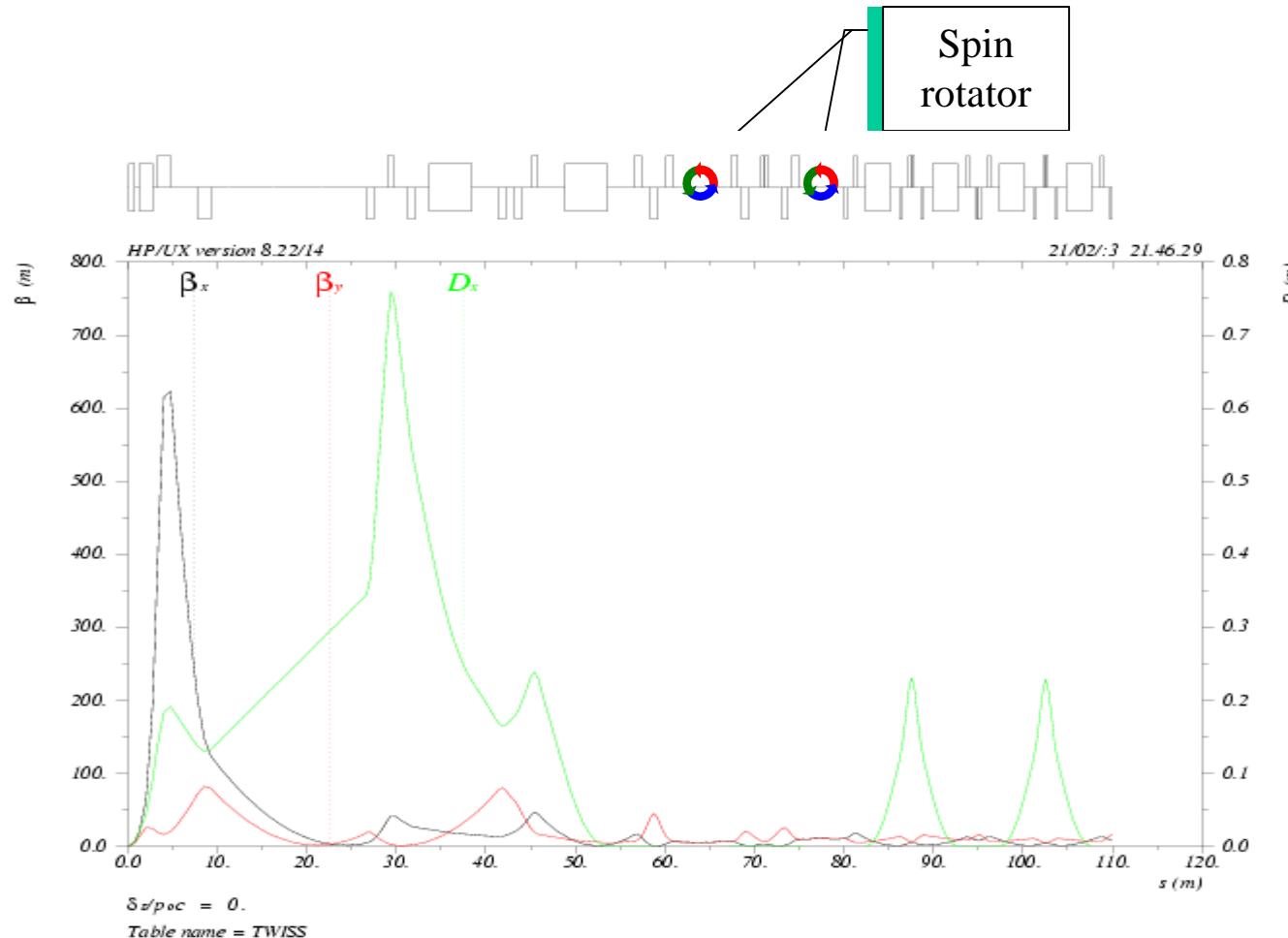


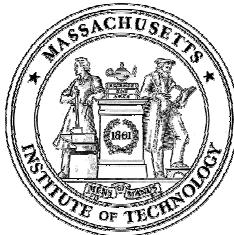
- **BINP-Bates 2002**
- The new arc lattice
(Low Emittance)



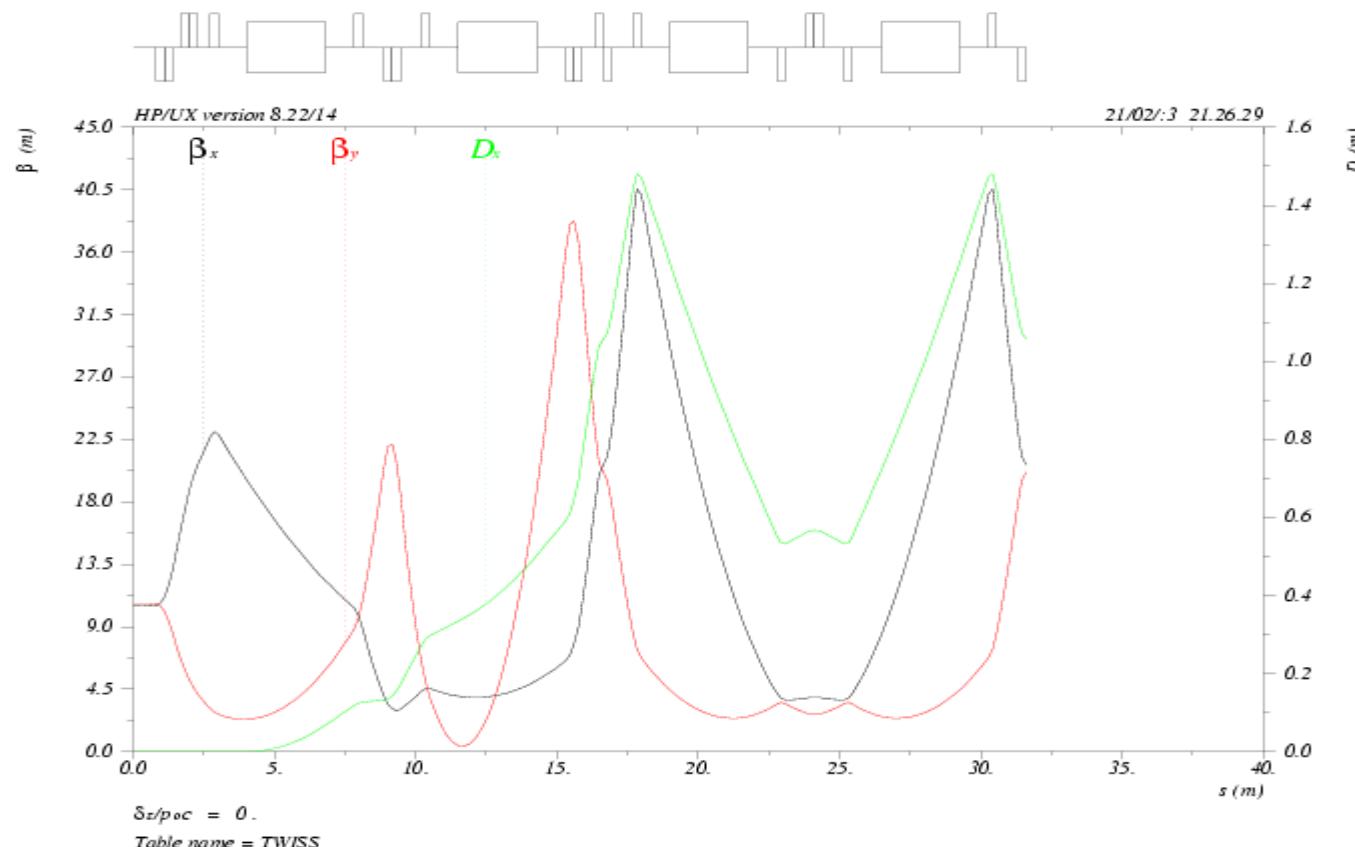


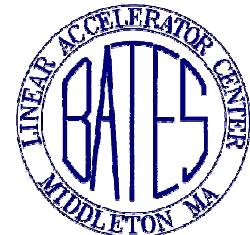
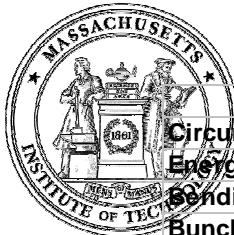
IR to normal cell, Low emittance.



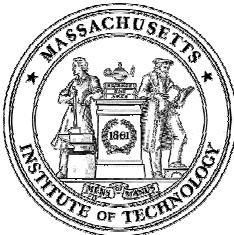


Normal cell to IR region, High emittance. (before solenoid spin rotator)

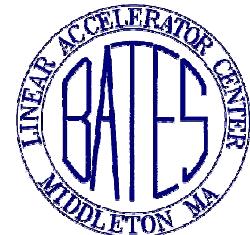




	New Arc 2003	BINP 02(sup. B)	SLAC HER	APS	ESRF
Circumference(m)	1199.17	958.65	2200.00	1104	884
Energy (GeV)	10	10	9	7	6
Bending radius(m)	68.755	58	165	38.96	23.37
Bunch Spacing (ns)	35.7	35.7	16.8/8.4/4.2		
Bunch spacing(m)	10.7	10.7			
Number of bunches	112.00	90.00	415/831/1658		
Bunch population	1.00E+11	1.00E+11			
Beam current(A)	0.45	0.45	3.00	0.3	0.2
Harmonic Number	1456	1169	3492		
RF frequency MHz	364	365.7	476	351.927	
Energy loss/turn (MeV)	12.87	15.26	3.52	5.45	4.91
	(+supper B) 21.26			(Insertion)1.2	
Accelarating voltage(MV)	30	30			
Total rad. Power(MW)	5.77	9.57(with S.B)	10.56		
Syn. Rad. Power/m (KW)	13.37	18.78	10.19	6.68	6.68
from normal bend					
Self-pola. T at 10GeV(minutes)	~15	~8.5			
Beam emittance (n m.rad)	8-160	65	50	8.2	4-7
Beta function at IP (cm)	8	10			
Beam size at IP(um)	25-113	80			
Momentum spread	1.00E-03	1.60E-03	6.00E-04		
Bunch length (cm)	0.9-4.0	2	1.1	0.58	
S.R. damping time(x) (mS)	6.2	4.2	37.7	9.5	7.2
	Low emit/High emit				Low emittance
Beta tune Ux	46.56/19.60	27.48		35.22	36.03
Beta tune Uy	31.61/15.62	21.9		14.3	11.065
Natural chromaticity x,y	LE: x=-112, y=-64	x=-76, y=-53		-112,-128	-124, -35
Luminosity $10^{33} \text{ cm}^{-2}\text{s}^{-1}$	1.36	0.58			
(10GeV e- x 250GeV P)					
(P emittance(95%) $12 \pi \mu\text{m}$)					



More works for the new arc lattice



- Chromaticity correction and dynamic aperture.
Possible dynamic aperture test at Bates SHR:
Low emittance lattice and harmonic correction sextupole families.
- Achievable polarization level and the sensitivity of polarization level to machine imperfections for all configurations.
Kinetic polarization test at Bates SHR.
- IR basic design: for different IR separation choices, re-examine the above evaluations.
- Path length adjustment for different proton velocity(energy) compensation.
- Further optimization based on more input from exp. and eng. considerations (magnet parameters etc.).